Longwave multiple scattering by clouds

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Clouds scatter radiation at all wavelengths of the spectrum. Single scattering parameters for cirrus ice particles (shown in Figure 1 for particle sizes of effective radius 5µm and 25µm) vary with wavelength and with particle size, and to a lesser extent with particle shape. To first order, cirrus single scattering parameters may be computed using Mie scattering theory for equivalent surface area spheres. More precise values can be obtained by using ray tracing or T-matrix calculations for nonspherical particle shapes. Differences between nonspherical (randomly oriented size distributions of right cylinders with aspect ratio of unity) and Mie scattering results are seen to vary with wavelength and particle size, and are clearly important in the solar spectral region. However, for thermal wavelengths the differences are small, particularly for flux and albedo calculations where the asymmetry parameter *g* can be used advantageously to represent the cloud phase function. For remote sensing applications the full phase function is required with its explicit angular dependence.

The spectral dependence of cloud multiple scattering is shown in Figure 2, where the cloud albedo R, direct and diffuse transmission T, and absorption A, have been integrated over solar zenith and emission angles, and are shown for an optical depth of □= 5, referenced at □ = 0.55_m. The solar shortwave part of the spectrum is characterized by single scattering albedo near unity for wavelengths less than 1 µm. Here, absorption A is near zero, and the albedo R increases monotonically with optical depth. Of note in the thermal part of the spectrum is the rather large reflectivity exhibited in the 10 – 20 µm region by the smaller size (5µm) particles which shifts toward longer wavelengths for larger (25µm) particles. Accordingly, a substantial amount of longwave radiation is reflected by clouds reducing the cirrus emissivity at these wavelengths by a (1 – R) factor. Also of note is the substantial amount of transmission within the same spectral region (mostly diffuse transmission) that persists to fairly large optical depths, particularly for the smaller size particles. All these effects directly impact the radiative throughput of clouds, and must the properly accounted for in GCM climate modeling simulations.

The effect of cloud multiple scattering on longwave radiation has been described in published literature. Differences as large as 20 W/m^2 have been attributed for the spectrally integrated longwave multiple scattering effect versus a no-scattering approximatin [e.g., *Ritter and Geleyn, 1992; Edwards and Slingo, 1996; Chou et al., 1999; Stephens et al., 2001*]. In GCM type context, *Stephens et al.* find the global mean difference to be 8 W/m^2. For modeling simplicity and minimization of computing time, most GCMs typically utilize a no-scattering type of radiative transfer to deal with thermal radiation. However, a global offset as large as 8 W/m^2 could substantially bias climate model sensitivity and its predictive results.

Detailed calculations show that the magnitude of the reported difference is an over-estimate, not because of deficiencies in the earlier multiple scattering calculations, but due to specification of their no-scattering reference – which was defined by setting the single scattering albedo to zero. A more accurate approximation for the no-scattering baseline is to set the asymmetry parameter to unity. This leads to selecting the cloud particle absorption cross-section rather than the extinction cross-section as the proper cross-section to be used in the subsequent radiative transfer calculations [e.g., *Paltridge and Platt, 1976*].

GCM parameterization of longwave cloud multiple scattering

For cloudy sky conditions, thermal fluxes in the GISS GCM are calculated without multiple scattering, using spectrally dependent Mie theory absorption cross-sections. These absorption cross-sections are spectrally re-distributed into non-contiguous k-distribution intervals in accord with the correlated k-distribution spectral intervals that are prescribed for the atmospheric gases (H_2O, CO_2, O_3, CH_4, N_2O, CFCs). The current GISS GCM version uses 33 correlated k-intervals tabulated as functions of pressure, temperature, and absorber amount. The non-scattering approximation is developed by setting the asymmetry parameter to unity whereby the cloud particle absorption cross-section can then be used to compute radiative transfer at thermal wavelengths and radiative heating and cooling rates with good accuracy. The no-scattering approximation results in significant computing cost savings without significant loss in accuracy compared to doubling/adding computations, which serve as an accurate reference for computing multiple scattering and thermal emission effects. The relatively small contribution due to multiple scattering by clouds at thermal wavelengths makes it possible to develop a simple parameterization can be applied at the cloud-top level to correct the no-scattering radiative fluxes for multiple scattering effects. The correction for multiple scattering effects to the outgoing radiation is included parametrically using tables that have been generated via off-line calculations.

The GCM cloud longwave scattering / emissivity parameterization is developed in three parts. First, a correction factor to the absorption optical depth is developed to correct the cloud layer transmission for the absence of diffuse transmission (which arises in the no-scattering approximation). This can be an important contribution to the outgoing thermal flux for finite optical depth clouds such as cirrus. Second, there is a cloud emissivity correction factor to correct the amount of thermal radiation that is emitted directly by the top cloud layer of the atmospheric column (in both the upward and downward directions). Third, tables of top cloud reflectivity (plane albedo) at thermal wavelengths are generated from off-line doubling/adding calculations and used to compute the contribution to the TOA flux that arises from the reflection of downwelling radiation incident at the cloud top level. A similar contribution is obtained for the upwelling radiation stream that is reflected downward at the bottom edge of the top cloud layer. This radiation flux contribution is added to the downwelling thermal flux below the atmospheric column bottom cloud level. Coefficients for the multiple scattering correction are tabulated as functions of cloud optical depth, particle size, liquid water / ice phase and cloud emission angle.

Implementation of the multiple scattering correction makes use of a three-point numerical quadrature (for $\mu = 1.0$, 0.5, and 0.1) to model the emission angle dependence of cloud reflectivity at thermal wavelengths. Tthe three-point numerical quadrature is also used to compute upward and downward radiative fluxes throughout the atmosphere. This approach provides improved accuracy for TOA radiative fluxes and stratospheric cooling rates relative to those obtained with two-stream multiple scattering formulations for which errors of order 10% are commonplace [e.g., *King and Harshvardhan, 1986*]. The numerical quadrature approach also provides angle dependent longwave radiances that can be used for diagnostic purposes and for more direct comparisons with satellite measurements.

Greenhouse forcing contributed by cloud LW multiple scattering

For a given atmospheric temperature distribution, the principal effect of multiple scattering is to reduce the outgoing thermal flux at the top of the atmosphere. The global magnitude of the effect is found to be relatively small – about 1.4 W/m^2 – but it is comparable to the 2.6 W/m^2 radiative forcing exerted by the increase in well mixed greenhouse gases (CO_2, CH_4, N_2O, CFCs) during the industrial era since 1850. The radiative forcing associated with LW cloud multiple scattering greenhouse contribution is not globally uniform. It closely follows the annual mean cloud distribution as shown in Figures 3 and 5. Radiative forcings in excess of 4 W/m^2 are seen to occur in persistently cloudy regions at northern latitudes between 40 – 60° N and also at the corresponding cloudy regions of the southern hemisphere. There is also enhanced greenhouse forcing due to the LW cloud multiple scattering greenhouse effect along the ITCZ and over the Tibetan plateau. In comparing Figures 3 and 5, it is apparent that the effect is primarily associated with total cloud distribution in mid to high latitudes, and with high clouds in the tropical regions as can be seen from Figure 6.

A reduction of outgoing TOA longwave flux results in trapping more heat energy within the troposphere, producing by definition an enhancement of the Earth's greenhouse effect. The largest contribution from the cloud multiple scattering effect arises primarily from the reduction in thermal emission from the cloud top region due to clouds having a non-negligible albedo at thermal wavelengths which limits the thermal emission from the cloud-top to (1 – R) of the Planck maximum. Due to the nature of multiple scattering, cloud albedo has a strong dependence on emission angle. Also, cloud reflectivity is reduced (and emissivity correspondingly increased) by the presence of atmospheric water vapor and other absorbing gases. Hence, cloud multiple scattering effects are less visible over low tropical clouds. There is in addition a reflected component of the downwelling flux that is incident on the cloud-top that is reflected upward to partially compensate for the reduction in cloud emissivity due to multiple scattering. However, this is typically a small contribution since the incident radiation originating from the upper atmosphere comes from a significantly colder temperature than the emission temperature of the cloud. In an isothermal atmosphere, the two components would cancel each other. For similar reasoning because of limited temperature differentials and the presence of gaseous absorption, multiple scattering effects between multiple cloud layers, and between clouds and the ground become diluted and thus in these regions tend to approach the results obtained without scattering.

Figure 4 shows the increase in the downwelling thermal flux at the ground level due to cloud longwave multiple scattering. Globally, this produces an increase in the downwelling flux at the ground surface – bottom of the atmosphere (BOA) by about 0.4 W/m^2. Most of this increase – sometimes as large as 1 W/m^2 – is preferentially distributed at high polar latitudes where the atmosphere is dry, so that upwelling flux from the ground that is reflected downward by at the cloud bottom can reach the ground surface without significant attenuation. The high Tibetan plateau stands out as an isolated continental region where there is enhanced downward flux due to longwave cloud scattering. In the tropics and mid latitudes the effect of tropospheric water vapor below the cloud bottom is to reduce the downwelling longwave cloud multiple scattering contribution to negligible proportions. This can be clearly seen in Figure 6.

References

Chou, M.-D., K.-T. Lee, S.-C. Tsay, and Q. Fu, Parameterization for cloud longwave scattering for use in atmospheric models. *J. Climate,* 12, 159-169, 1999.

Edwards, J.M. and A. Slingo, Studies with a flexible new radiation code. I; Choosing a configuration for a large-scale model. *Q. J. R. Meteorol. Soc.,* 122, 689-719, 1996.

King, M. D. and Harshvardhan, Comparative accuracy of selected multiple scattering approximations, *J. Atmos. Sci.,* 43, 784-801, 1986.

Paltridge, G. W. and C. M. R. Platt, *Radiative Processes in Meteorology and Climatology*, Elsevier Scientific Publishing Co., Amsterdam, 1976.

Ritter, B. and J.F. Geleyn, A comprehensive radiation scheme for numerical weather prediction models with potential application in climate simulations. *Monthly Wea. Rev.,* 120, 303-325, 1992.

Stephens, G. L., P. M. Gabriel, and P. T. Partain, Parameterization of atmospheric radiative transfer. Part I: Validity of simple models. *J. Atmos. Sci.,* 58, 3391-3409, 2001.

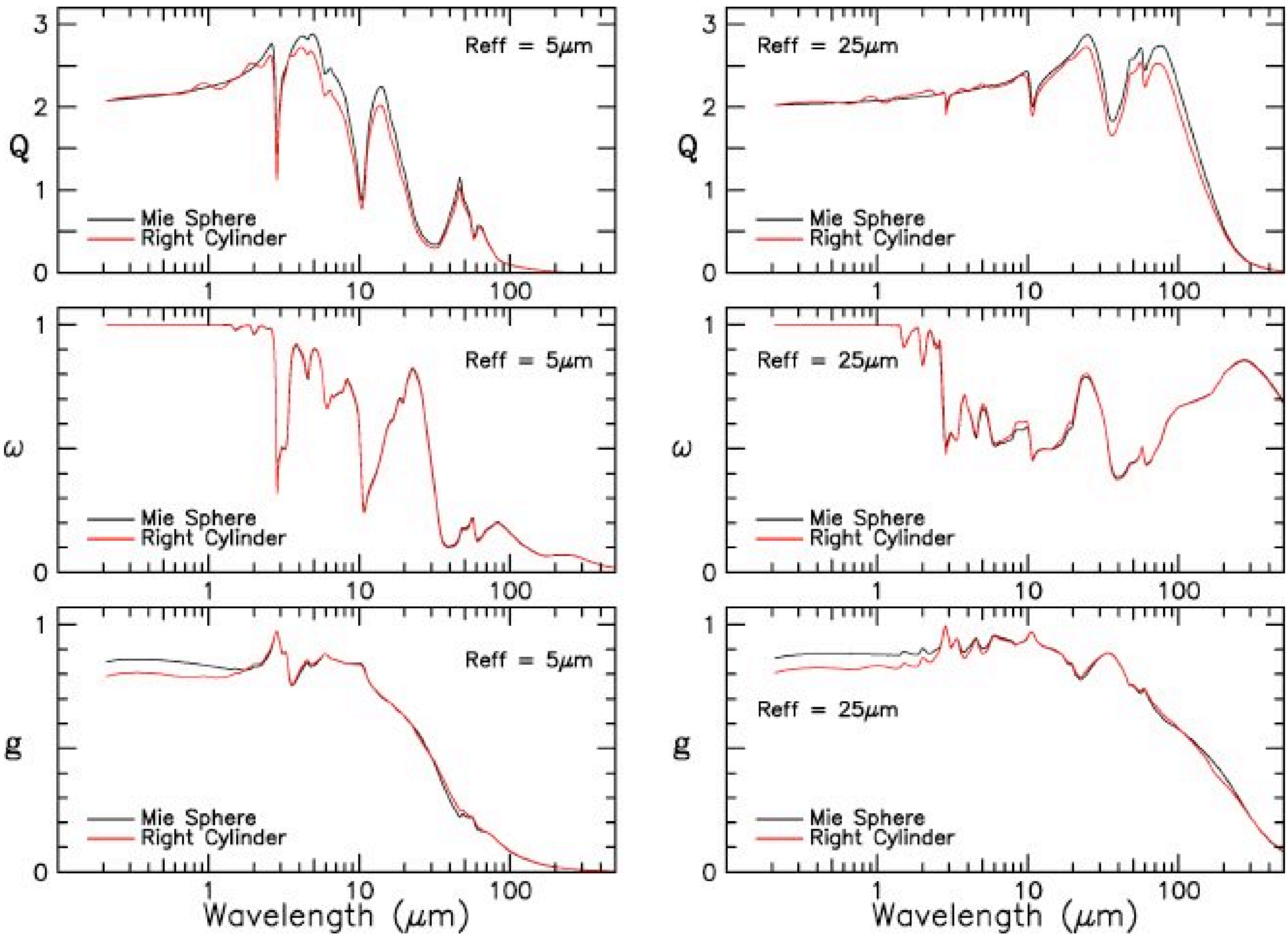

Figure 1. Single scattering parameters (Q, _o, g) for cirrus particle sizes of effective radius 5 _m and 25 _m.

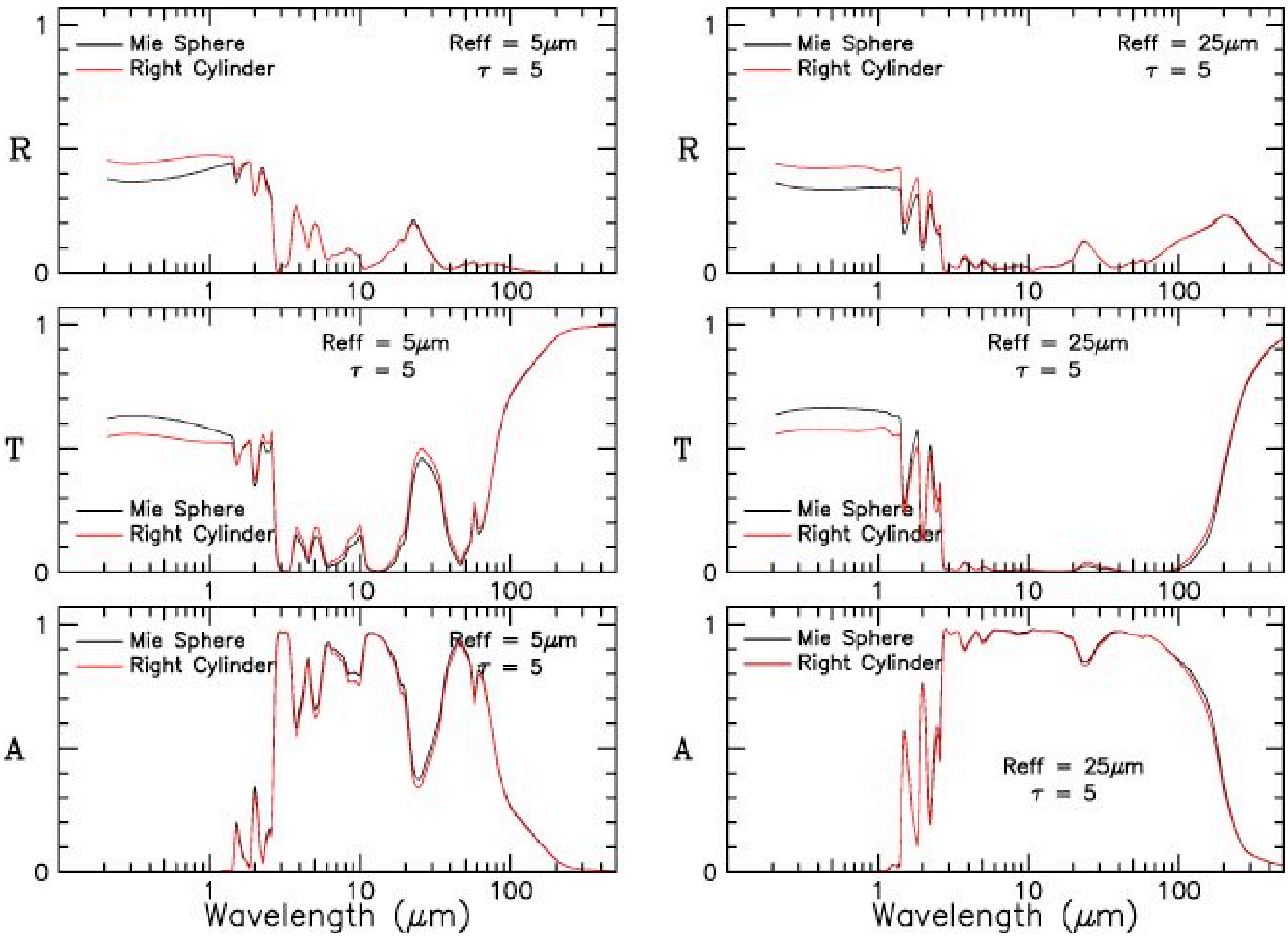

Figure 2. Multiple scattering properties (R,T,A) for cirrus of _=1 and particle sizes of effective radius 5 _m and 25 _m.

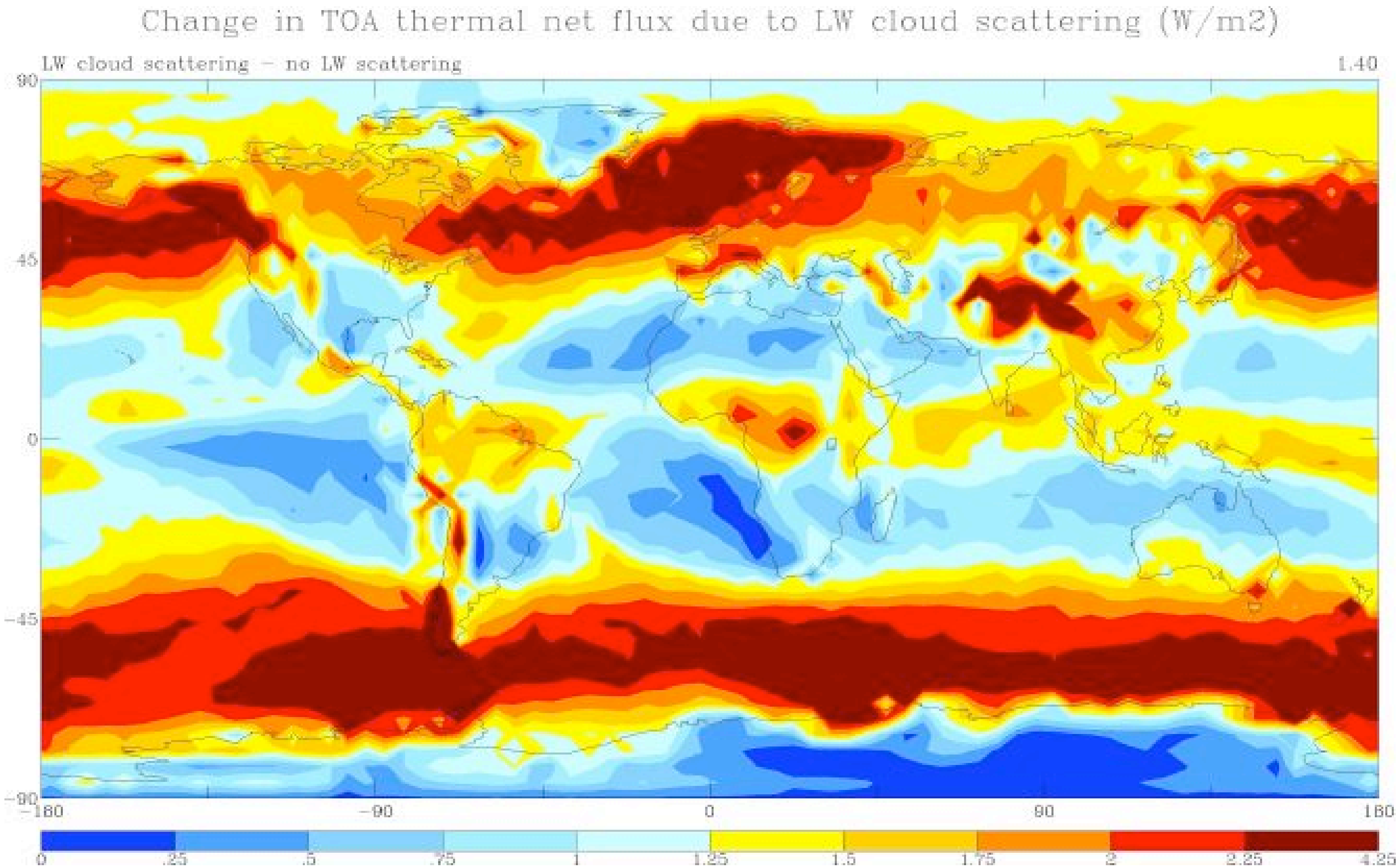

Figure 3. Change in TOA thermal outgoing flux due to longwave cloud scattering. The TOA fluxes are computed using the standard GISS 4° 5° GCM control run with the SI200 radiation. Since outgoing fluxes are typically larger for the no-scattering approximation, the flux difference representing greenhouse forcing due to longwave cloud multiple scattering is shown as a positive quantity. The global annual mean greenhouse forcing due to longwave cloud multiple scattering is 1.4 W/m^2.

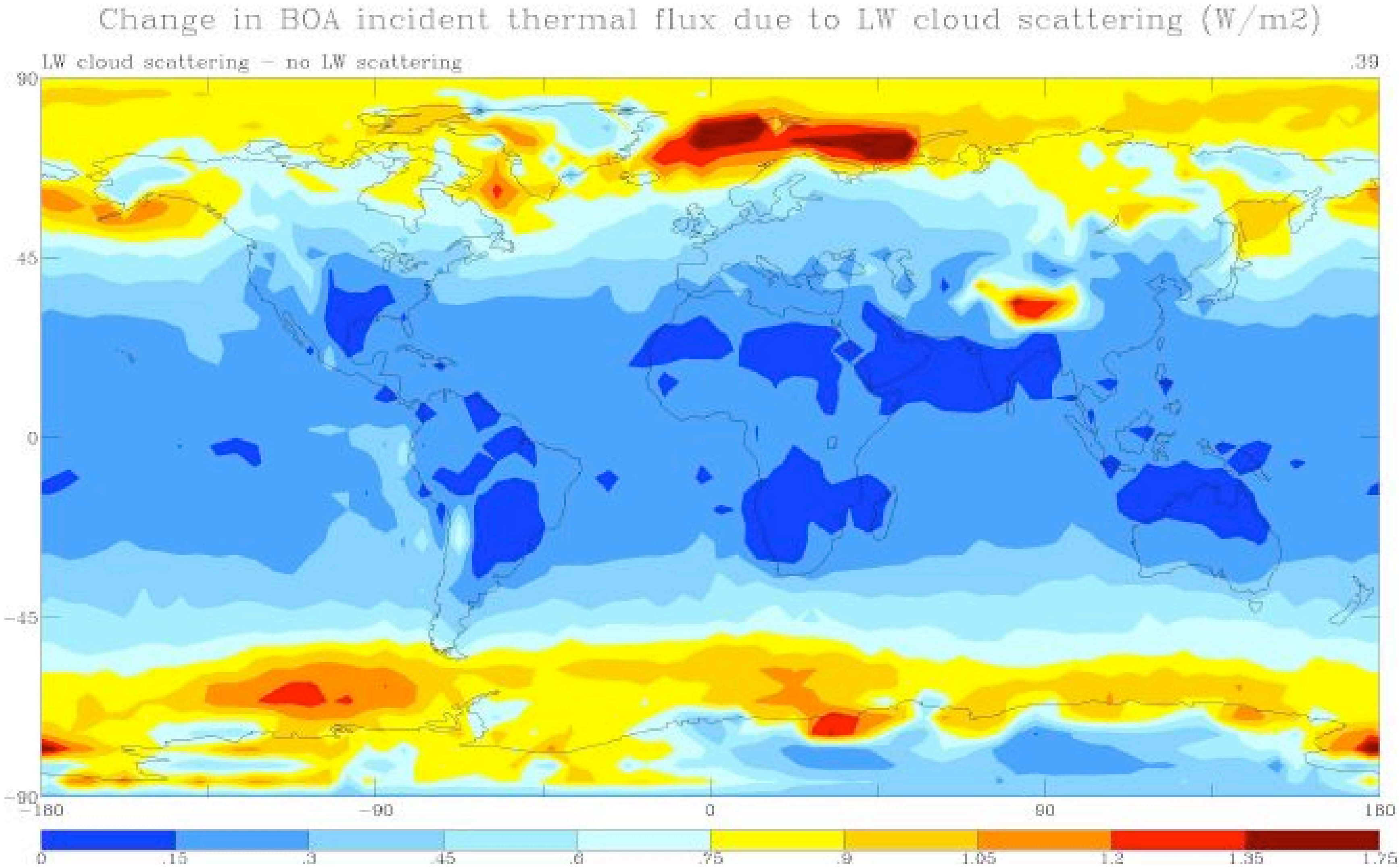

Figure 4. Change in BOA incident thermal flux due to longwave cloud scattering. The BOA fluxes are computed using the standard GISS 4° 5° GCM control run with the SI200 radiation. Downwelling flux enhancement by downward reflection of upwelling radiation due to the longwave cloud multiple scattering effect is shown as a positive quantity. The global annual mean BOA incident flux increase due to longwave cloud multiple scattering is 0.39 W/m^2.

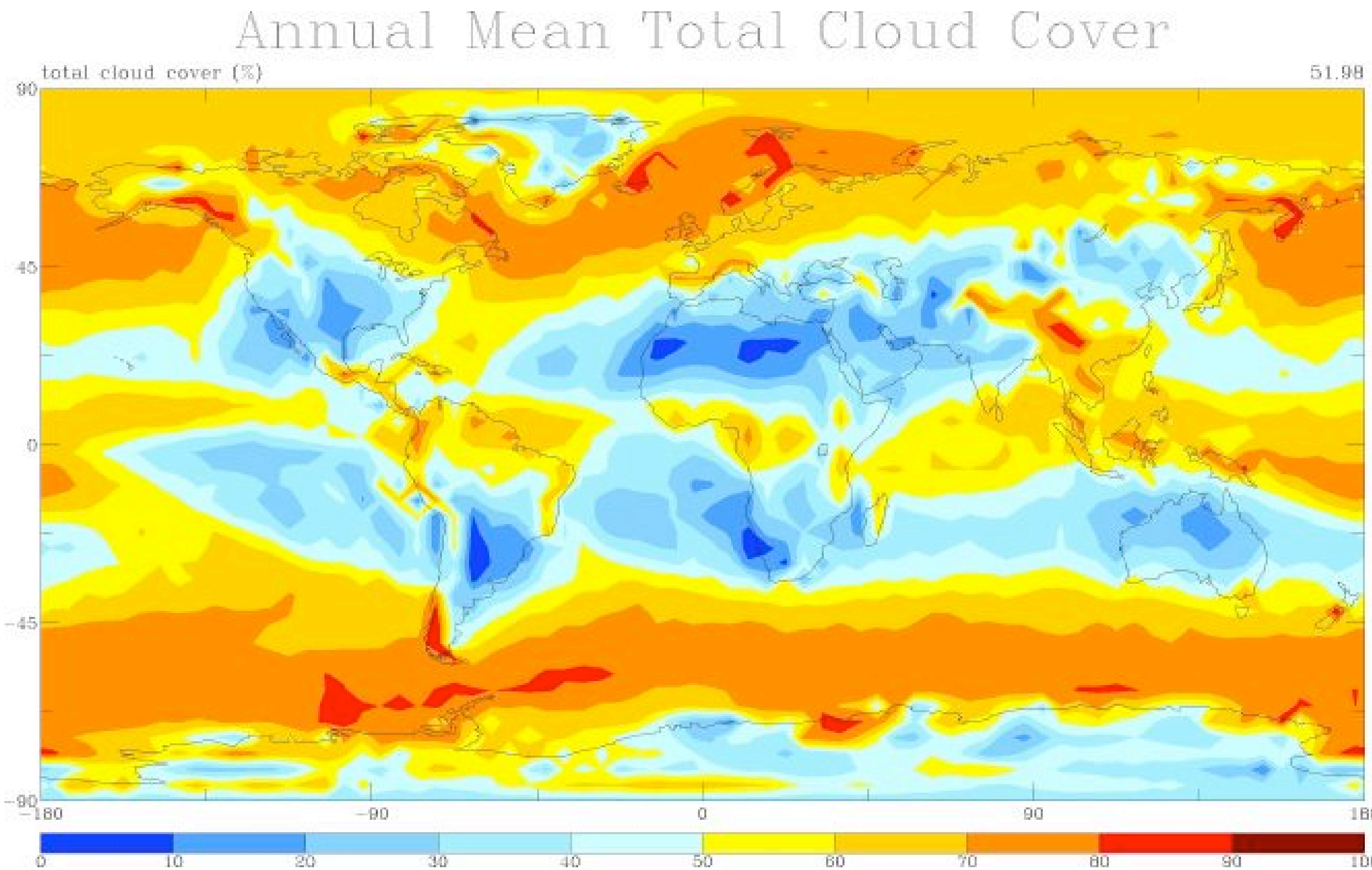

Figure 5. Annual mean total cloud cover as computed using the standard GISS 4°5° GCM control run with the SI200 radiation. The global annual mean total cloud cover is 52 %.

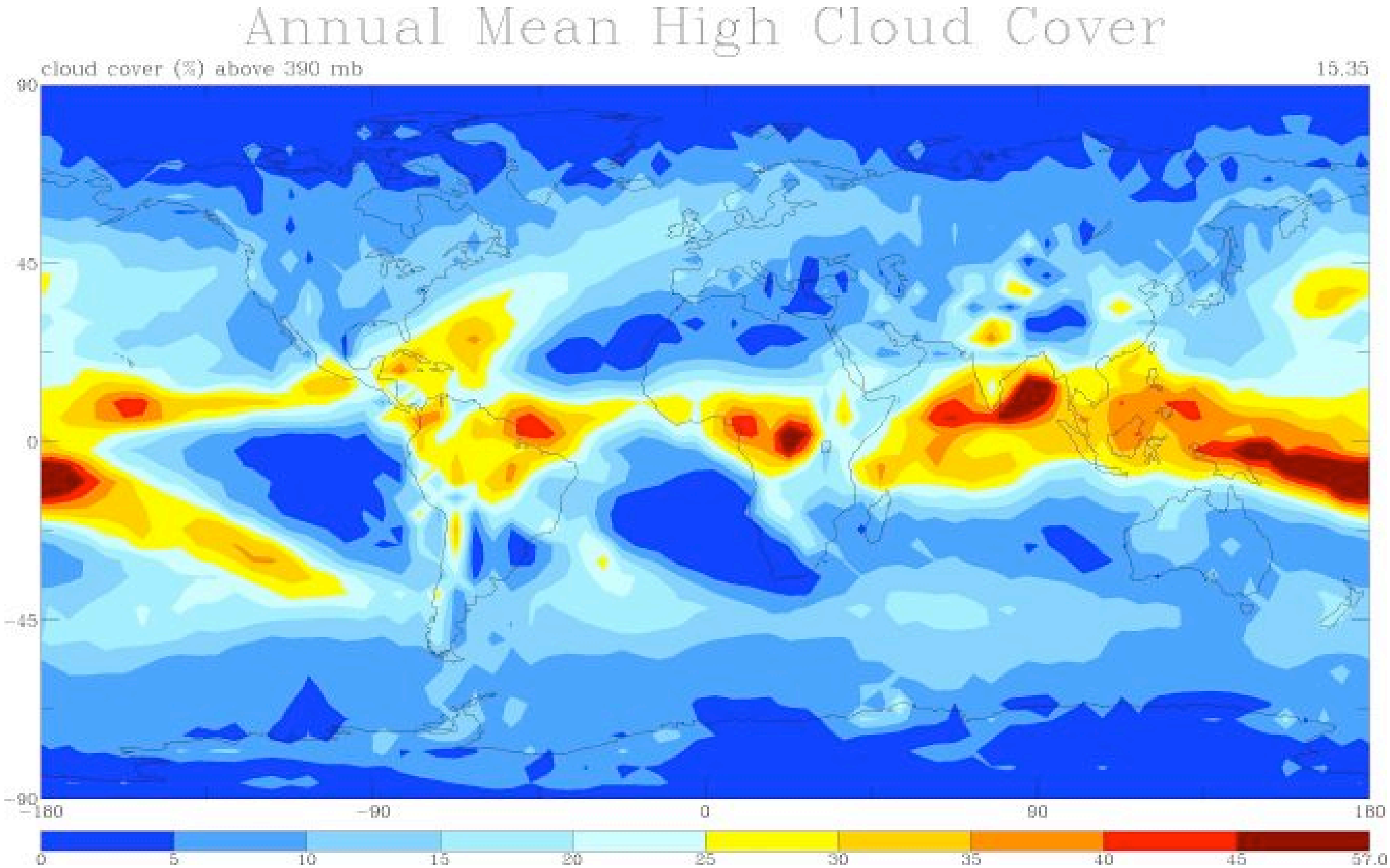

Figure 6. Annual mean high cloud cover as computed using the standard GISS 4°􏰂 5° GCM control run with the SI200 radiation. The global annual mean cloud cover for clouds with cloud tops above 390 mb is 15.35 %.